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Characterization of Solar Cells for Space Applications

Volume III. Electrical Characteristics
of OCLI Hybrid MLAR Solar Cells as a
Function of Intensity and Temperature

R. G. Downing
R. S. Weiss

(NASA-CR-157605) CHARACTERIZATION OF SOLAR
CELLS FOR SPACE APPLICATIONS. VOLUME 3:
ELECTRICAL CHARACTERISTICS OF OCLI HYBRID
MLAR SOLAR CELLS AS A FUNCTION OF INTENSITY
AND TEMPERATURE (Jet Propulsion Lab.) 39 p G3/44

N78-32545

Unclas
30324

September 1, 1978

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California



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PREFACE

The work described herein was performed by the Control and Energy Conversion Division of the Jet Propulsion Laboratory.

ACKNOWLEDGMENT

The authors gratefully acknowledge the invaluable assistance of Lois Fite and James Hix who wrote the computer programs for performing the data analysis and curve plotting.

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ABSTRACT

Electrical characteristics of hybrid multilayer antireflectance coated N/P silicon solar cells are presented in graphical and tabular format as a function of solar illumination intensity and temperature.

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SECTION I

INTRODUCTION

A series of reports is being generated to present parametric characterization data on both state-of-the-art and developmental solar cells of interest to the photovoltaic community. These data consist of the electrical characteristics of the candidate solar cell under a wide range of temperature and illumination intensity combinations of the type encountered in typical space applications. This series (JPL 78-15) will consist of a number of reports, each report being devoted to a particular type of solar cell and identified by a volume number. Previously published reports with their associated solar cell descriptions are listed in the bibliography to this document. Each report consists primarily of working graphs and tables and does not address itself to interpretive conclusions. The formatting of this series of reports will be relatively invariant to facilitate comparisons between the characteristics of any of the cell types considered in the series. This report contains a set of parametric data on the OCLI hybrid multilayer antireflectance-coated solar cell which is commercially available.

SECTION II

CELL DESCRIPTION

The cells reported here were manufactured by Optical Coating Laboratories, Inc. (OCLI), and are available as off-the-shelf space-qualified solar cells. These cells are fabricated from crucible-grown, P-type silicon, boron-doped to a nominal resistivity of 10 ohm-cm. The cell dimensions are 2 cm by 2 cm by 0.025 cm (10 mils) thick. A multilayer antireflectance coating is applied to the top surface. The electrical contact on the top surface consists of solderless Ti-Pd-Ag in an eight-finger grid pattern with a bus bar running the length of one side. The rear contact is a picture frame contact of the same material.

In order to obtain parametric test data consistent with typical space applications, cover slides were mounted on the cells prior to testing. The cover slides were 7940 fused silica 0.015 cm (6 mils) thick with an 0.35 micrometer cut-on dielectric interference filter. The cover slides were bonded to the surface of the cells with Dow-Corning 162 silicone adhesive.

SECTION III

TEST PROGRAM

The solar cells were mounted on a copper test plate using RTV 560. The test plate was, in turn, mounted to a heat sink with provisions

for both heating and cooling so that the cells could be maintained at the desired temperature independent of the solar intensity. All testing was carried out in a vacuum at a pressure of less than 1×10^{-6} torr.

The illumination source used was a Spectrolab Model X-25 Mark II Spectrosun filtered solar simulator. This simulator uses an optical integrator lens in the optical system which uniformly distributes a relatively collimated light beam at specific distances from a 2.5 kW short-arc xenon lamp. A system of filters modifies the spectral distribution so that it approximates that of space sunlight. The light beam provides a pattern having a uniformity of $\pm 1\%$ over an area of 225 cm^2 at the test plane. Illumination intensity is varied by position of the simulator in combination with transmission filters. The solar simulator beam is introduced into the vacuum chamber through a window of 7940 fused silica. The solar intensity and spectral integrity of the solar simulator are constantly monitored and maintained using space calibrated standard cells obtained with the NASA/JPL solar cell balloon flight standardization program. Photographs of the solar cell, the assembled plate, and the experimental characterization test facility are shown in Figures A-1 through A-4 of the appendix.

The temperature range covered in these measurements was -160°C to 140°C while the solar intensity range covered was 5 mW/cm^2 to 250 mW/cm^2 . The data were taken at each environment point in the matrix in the form of an I-V curve. The appropriate parameters were then read from the I-V curves and punched on cards for the computer analysis and curve plotting functions. The cell temperature was monitored by a thermocouple attached to the surface of a separate cell mounted with the cells under test. Prior, intermediate, and post test ambient measurements were performed daily to ensure that the accuracy and stability of the test equipment and the test specimens themselves were maintained within $\pm 2\%$ during the course of the testing program.

SECTION IV

DISCUSSION OF RESULTS

A computer program computes statistical averages and standard deviations with respect to the measured cells for each intensity-temperature measurement condition. It then produces summary tables, as shown in Tables 1 to 7, that display averages and standard deviations of the cell characteristics in a two-dimensional array format, one dimension representing cell temperature and the second dimension representing incoming light intensity (AMO spectrum). The program then produces plots of the various electrical parameters of interest, with either incident intensity or cell temperature as the independent variable, as shown in Figures 1 to 14. Least square fits to the data points are then made automatically to the measured data points using a second-degree polynomial for most parameters. The V_{oc} and V_{mp} data points are fit with a linear equation. The curve factors and AMO efficiencies are not fit but are interconnected from point to point. In addition, the program calculates the temperature

coefficients of the pertinent cell electrical parameters of interest, using the aforementioned curve fits, and plots these as a function of temperature, with intensity as a parameter. This is shown in Figures 15 through 18.

The figures are intended to be working artifacts; that is, they are formatted in such a way that they can supply information of a general nature or may be used to generate predictions, comparisons, computer input data, etc. To facilitate comparisons and inputting, all units are standardized as follows:

- (1) All currents are in units of mA/cm^2 .
- (2) All voltages are in units of mV.
- (3) All power outputs are in units of mW/cm^2 .
- (4) All curve factors are in dimensionless units.
- (5) All efficiencies are in percentages and are based on total cell area.
- (6) All temperatures are in $^{\circ}\text{C}$.
- (7) All incoming intensities are in units of mW/cm^2 and are representative of an AMO spectrum.
- (8) All geometric dimensions are in units of cm or μm (whichever is most convenient conceptually.)

The tables included in this report contain complete numerical information with respect to the average values of the following solar cell electrical parameters: I_{sc} , V_{oc} , I_{Pmax} , P_{max} , CF, and efficiency at each intensity-temperature combination. For each such parameter at each such intensity-temperature combination, the standard deviation is presented to provide estimates of statistical validity. All current and power output data are on the basis of unit area derived by dividing measured output by total cell area. All solar cell efficiency numerical data are based on total cell area.

The OCLI hybrid MLAR solar cell is a commercially available device that can be considered for space applications. OCLI has recently added the MLAR concept to its violet solar cell which will be evaluated and reported here at a later date.

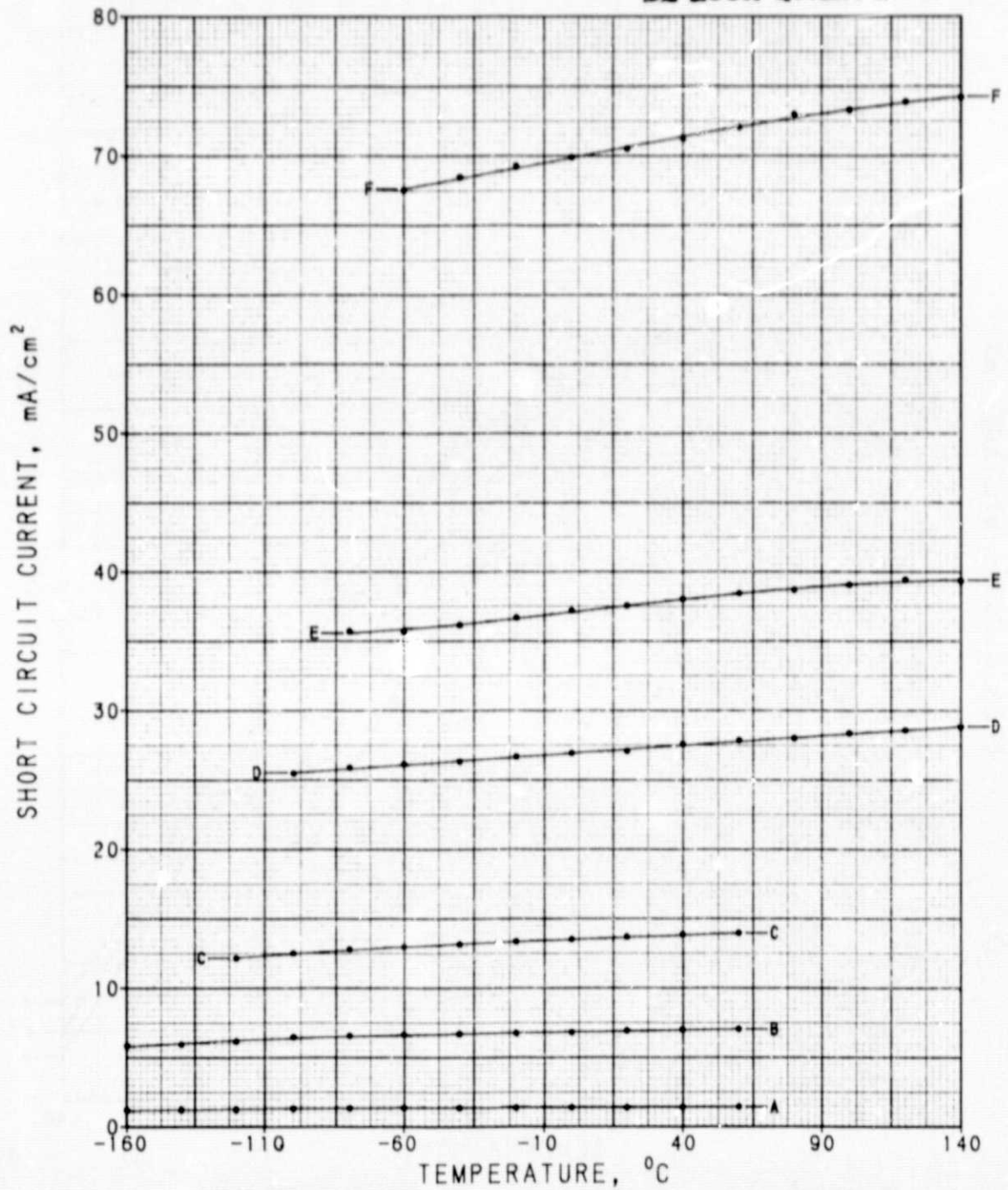
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Volume I. Electrical Characteristics of OCLI Violet Solar Cells as a Function of Intensity and Temperature, March 1978

Volume II. Electrical Characteristics of Solarex 50 Micron Solar Cells as a Function of Intensity and Temperature, August 1978

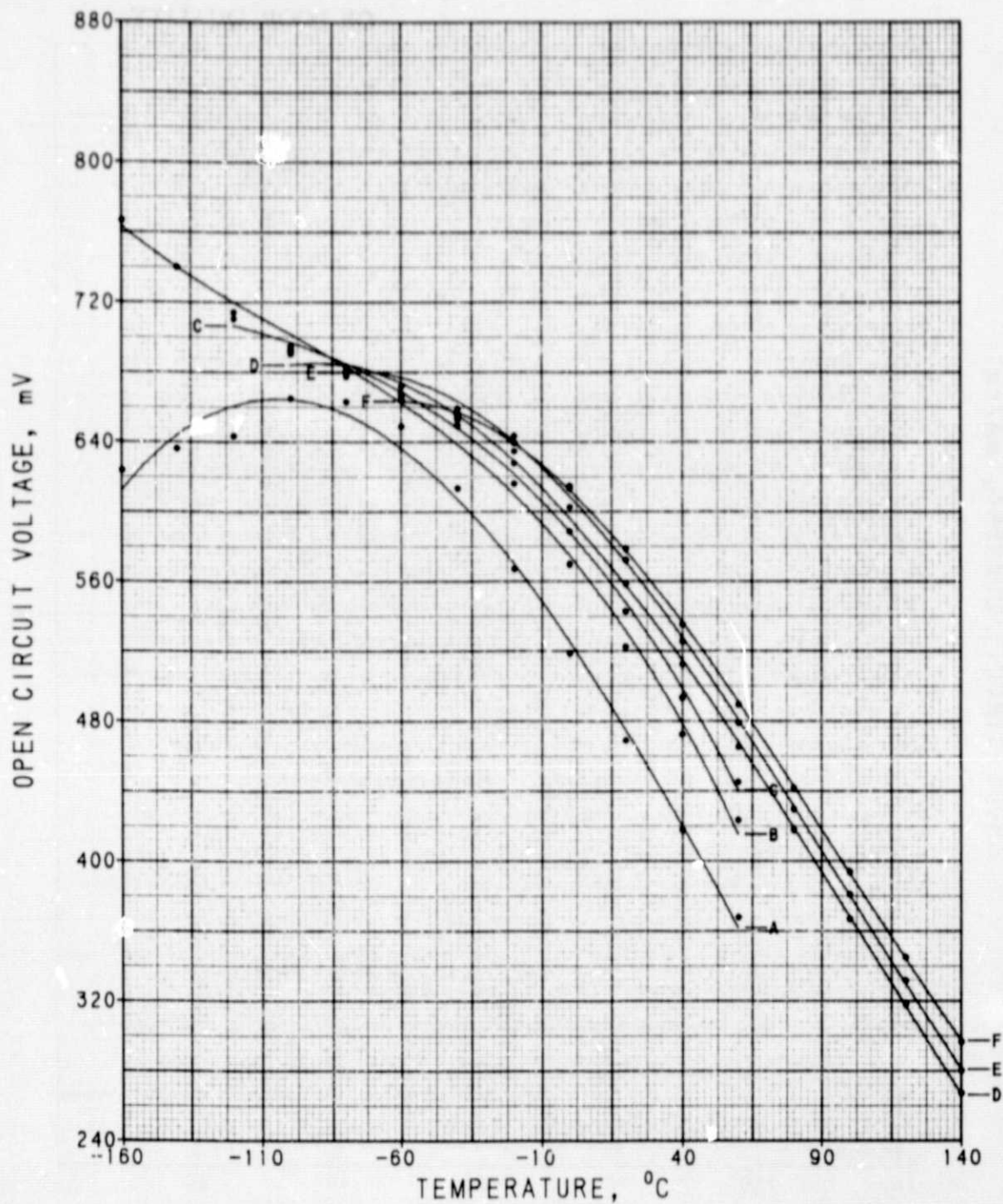
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ID	mW/cm²
A	5.0
B	25.0
C	50.0
D	100.0
E	135.3
F	250.0

OCLI (HYBRID MLAR)
N⁺ 10 OHM-CM CG SILICON
2 X 2 X .025 CM
TI-PD-AG CONTACTS 8 LINES
MULTI-LAYER (GREEN) AR COATING
7940 COVER .35 MICRON CUT-ON
.015 CM THICK
SAMPLE SIZE 14

Figure 1. Average I_{sc}/cm^2 as a Function of Temperature

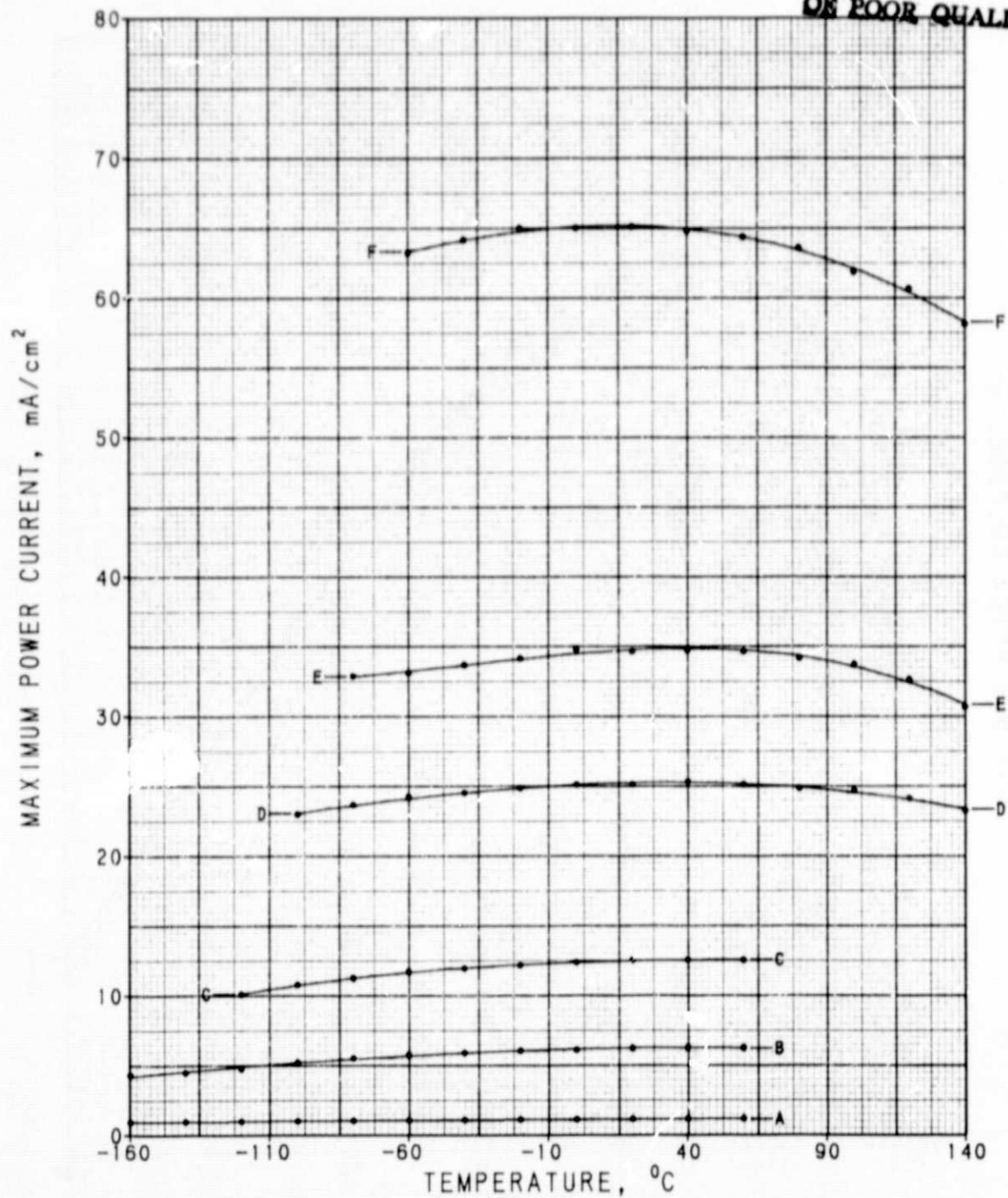


ID	mW/cm ²
A	5.0
B	25.0
C	50.0
D	100.0
E	135.3
F	250.0

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

Figure 2. Average V_{OC} as a Function of Temperature

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ID	mW/cm ²
A	5.0
B	25.0
C	50.0
D	100.0
E	135.3
F	250.0

OCLI (HYBRID MLAR)
N/P 10 OHM-CM CG SILICON
2 X 2 X .025 CM
TI-PD-AG CONTACTS 8 LINES
MULTI-LAYER (GREEN) AR COATING
7940 COVER .35 MICRON CUT-ON
.015 CM THICK
SAMPLE SIZE 14

Figure 3. Average I_{mp}/cm^2 as a Function of Temperature

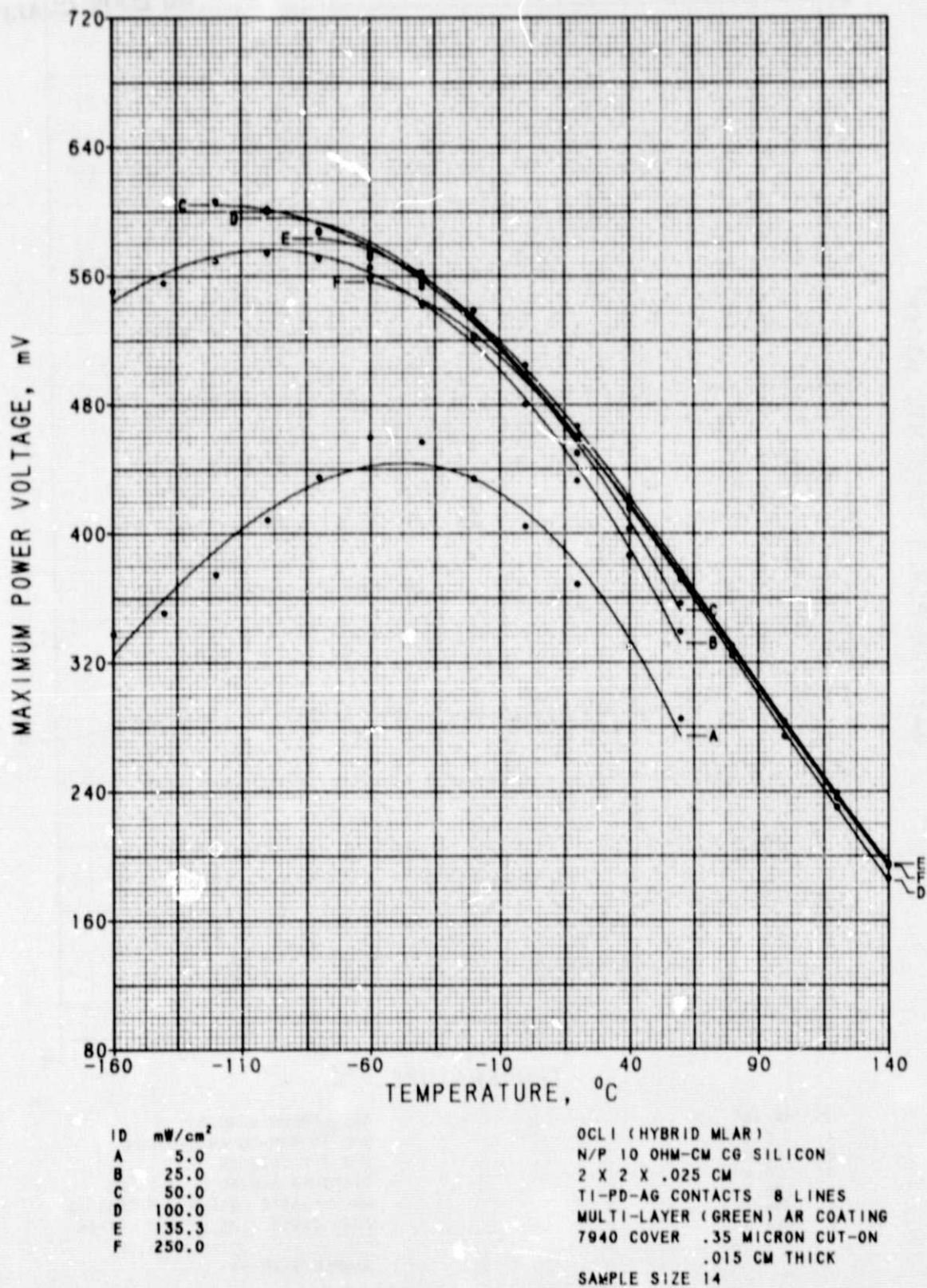
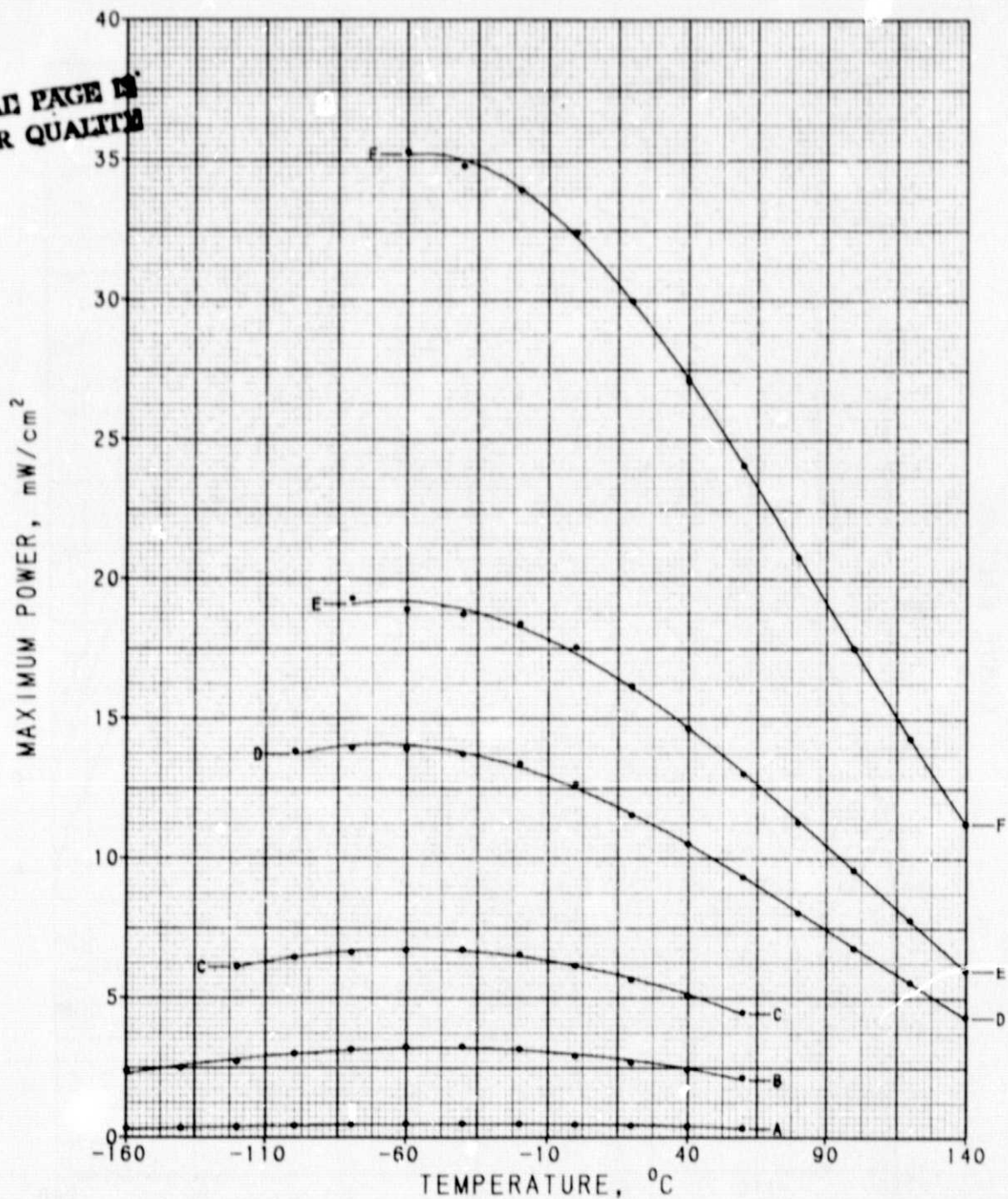


Figure 4. Average V_{mp} as a Function of Temperature

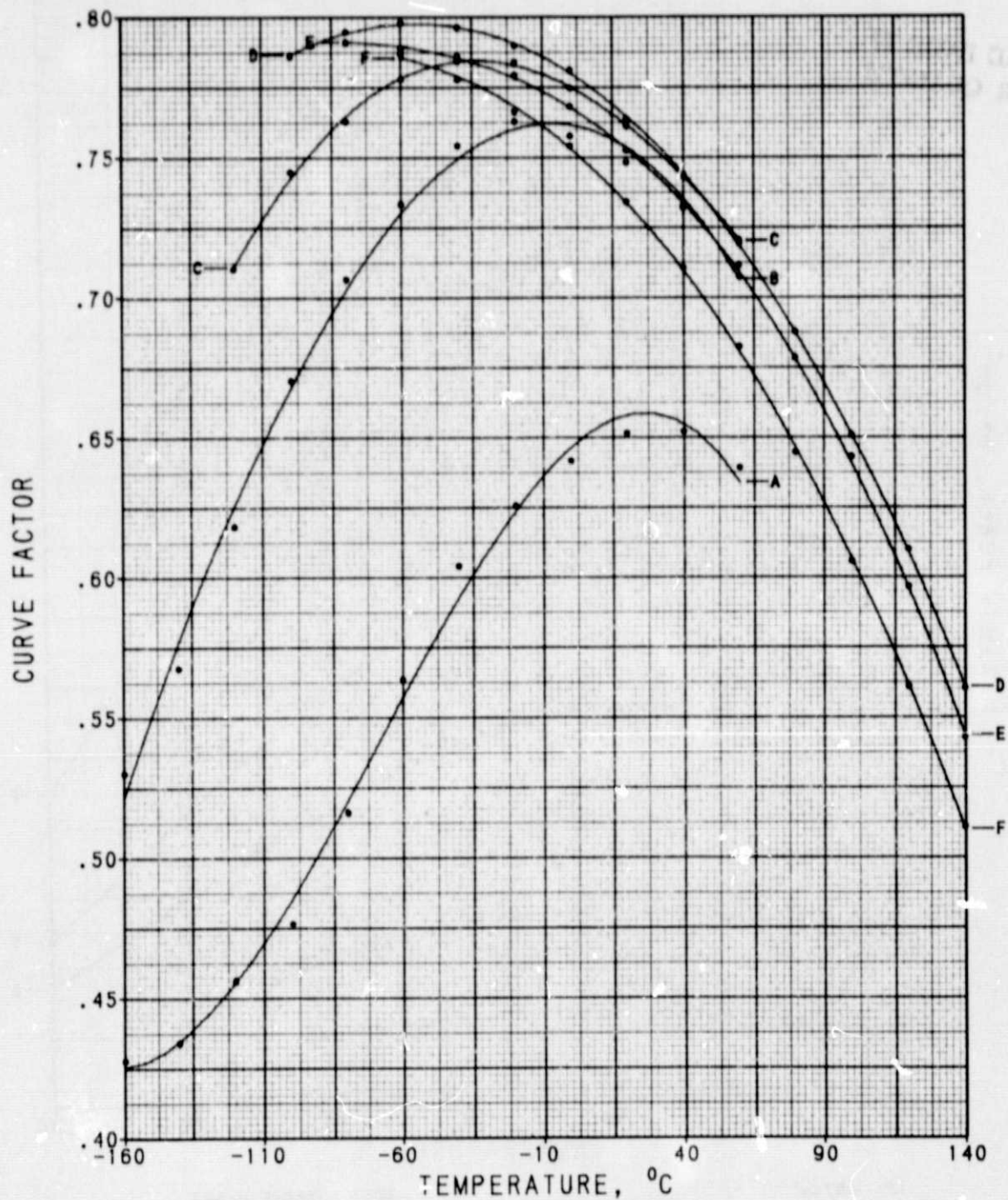
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ID	mW/cm ²
A	5.0
B	25.0
C	50.0
D	100.0
E	135.3
F	250.0

OCLI (HYBRID MLAR)
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7940 COVER .35 MICRON CUT-ON
.015 CM THICK
SAMPLE SIZE 14

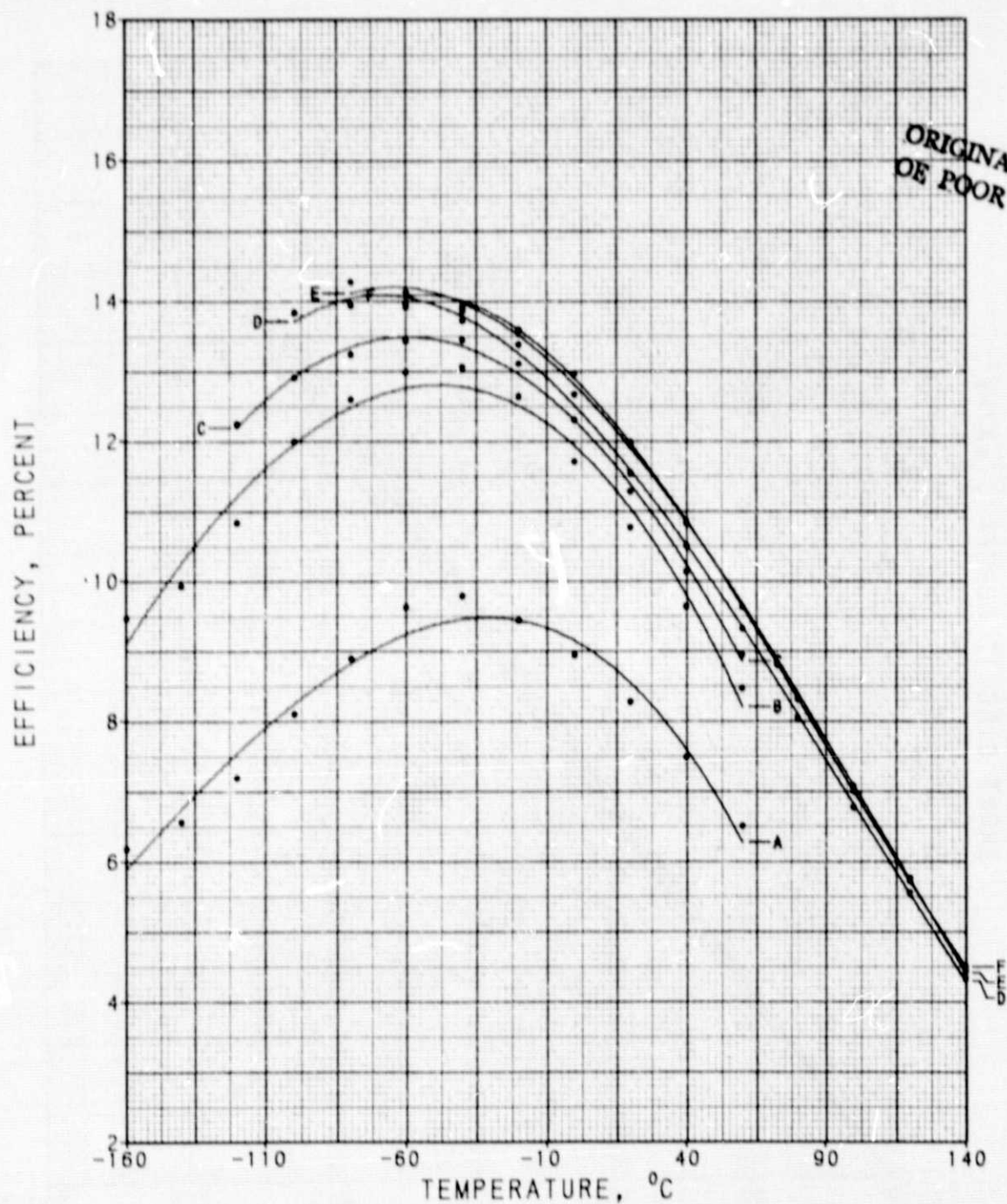
Figure 5. Average $P_{\max}/\text{cm}^2$ as a Function of Temperature



ID	mW/cm ²
A	5.0
B	25.0
C	50.0
D	100.0
E	135.3
F	250.0

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

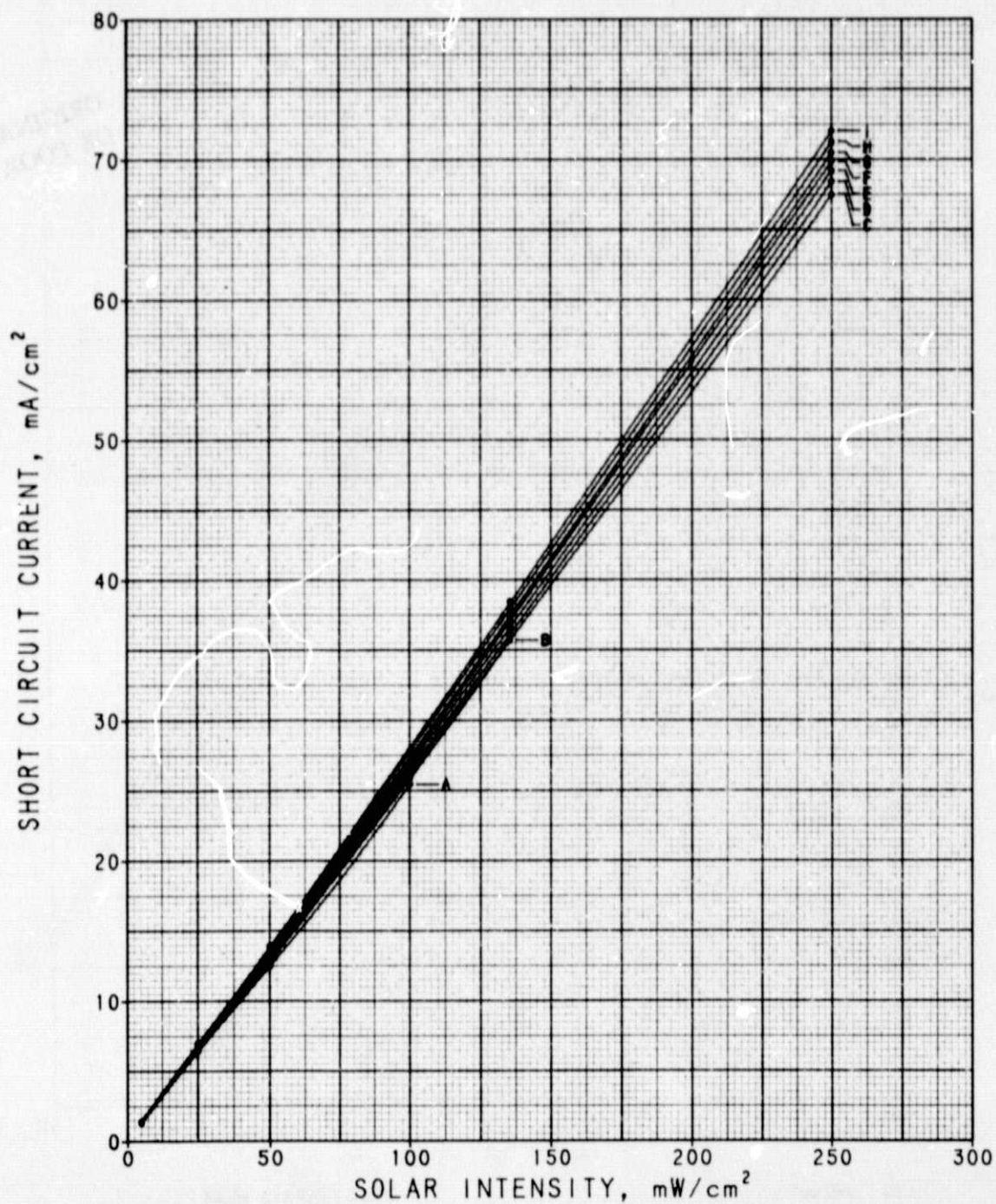
Figure 6. Average Curve Factor as a Function of Temperature



ID mW/cm²
 A 5.0
 B 25.0
 C 50.0
 D 100.0
 E 135.3
 F 250.0

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

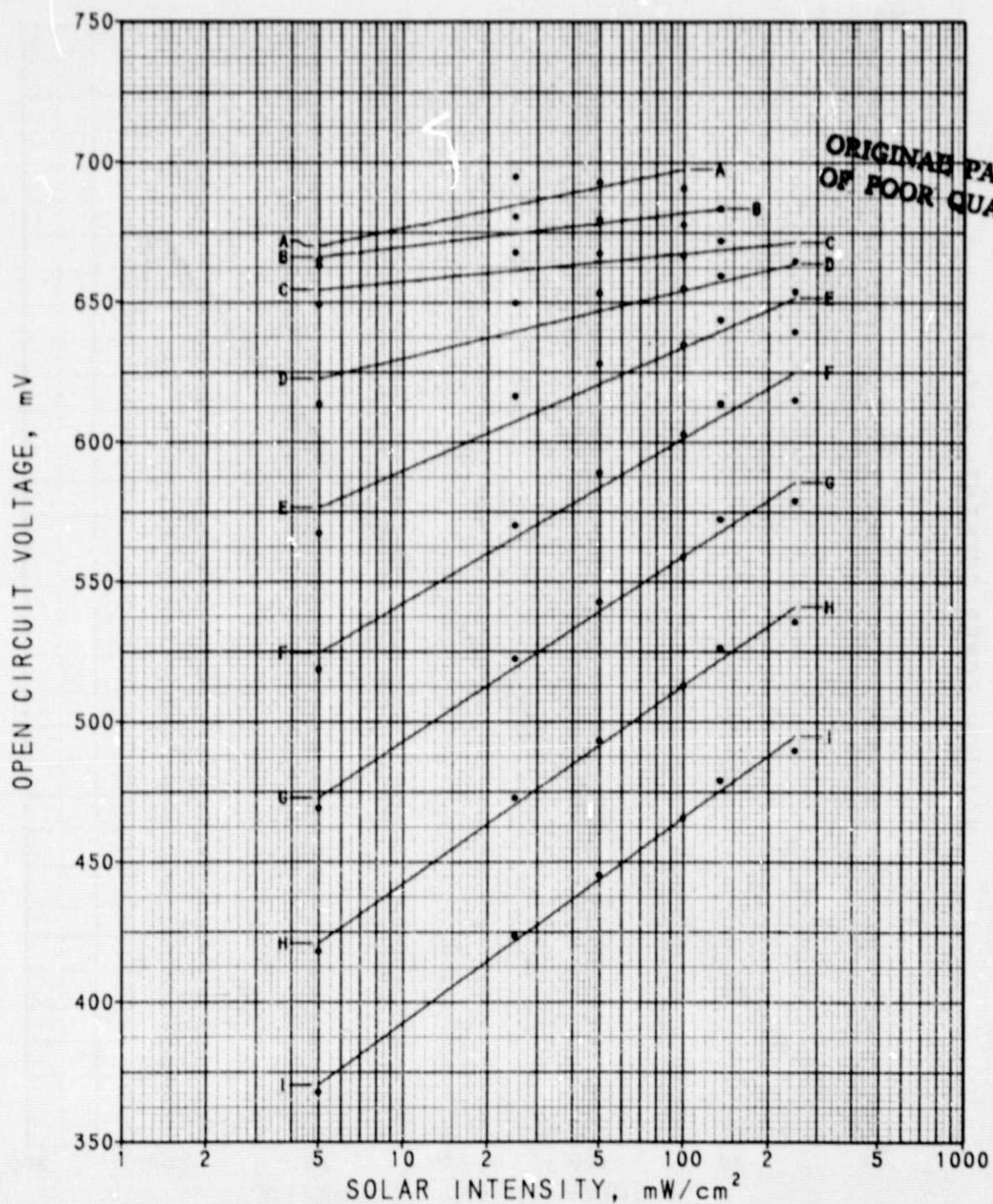
Figure 7. Average AMO Efficiency as a Function of Temperature



ID	°C	ID	°C
A	-100.0	I	60.0
B	-80.0		
C	-60.0		
D	-40.0		
E	-20.0		
F	.0		
G	20.0		
H	40.0		

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CP SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

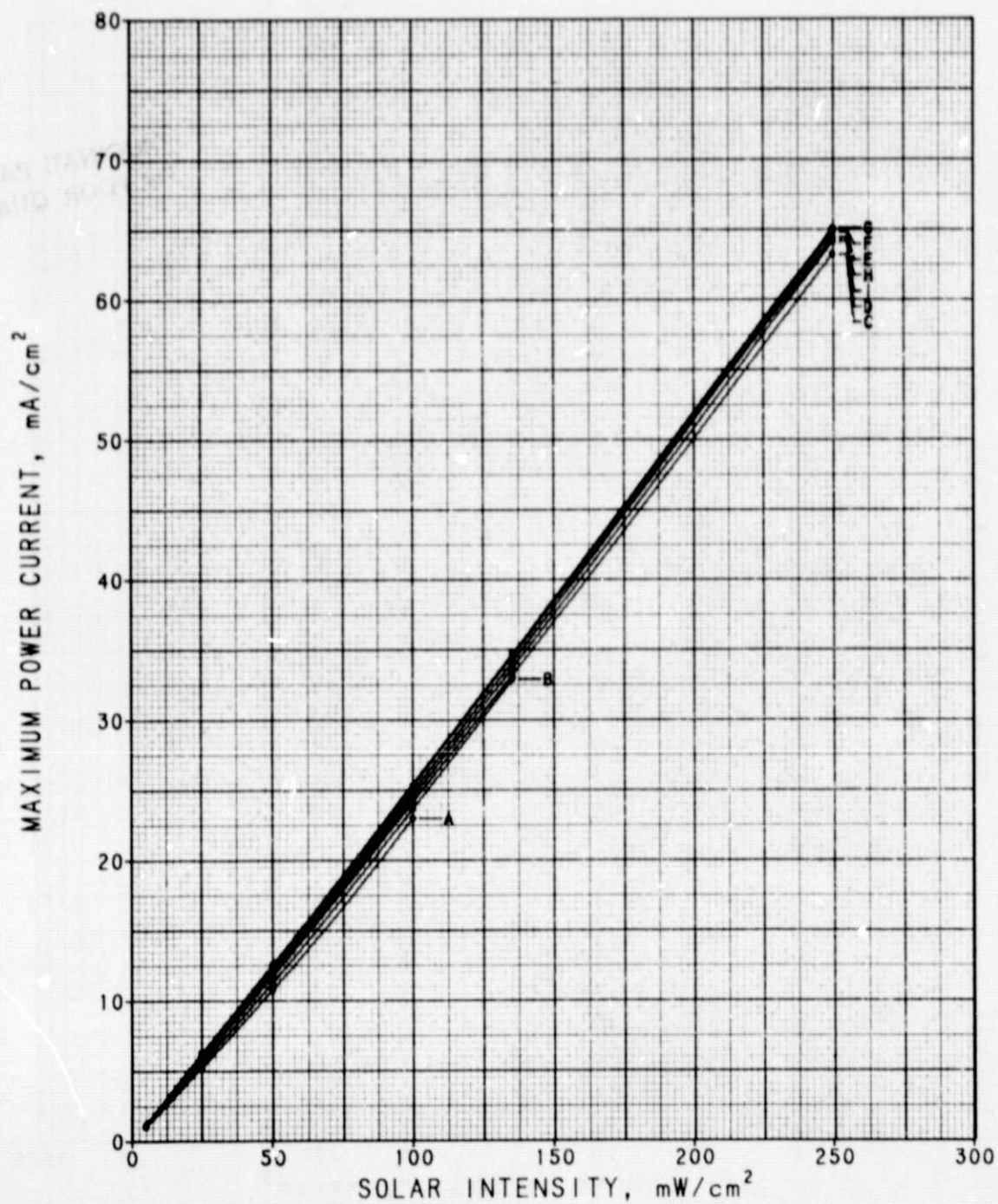
Figure 8. Average I_{SC}/cm^2 as a Function of Intensity



ID	°C	ID	°C
A	-100.0	I	60.0
B	-80.0		
C	-60.0		
D	-40.0		
E	-20.0		
F	0.0		
G	20.0		
H	40.0		

OCL1 (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

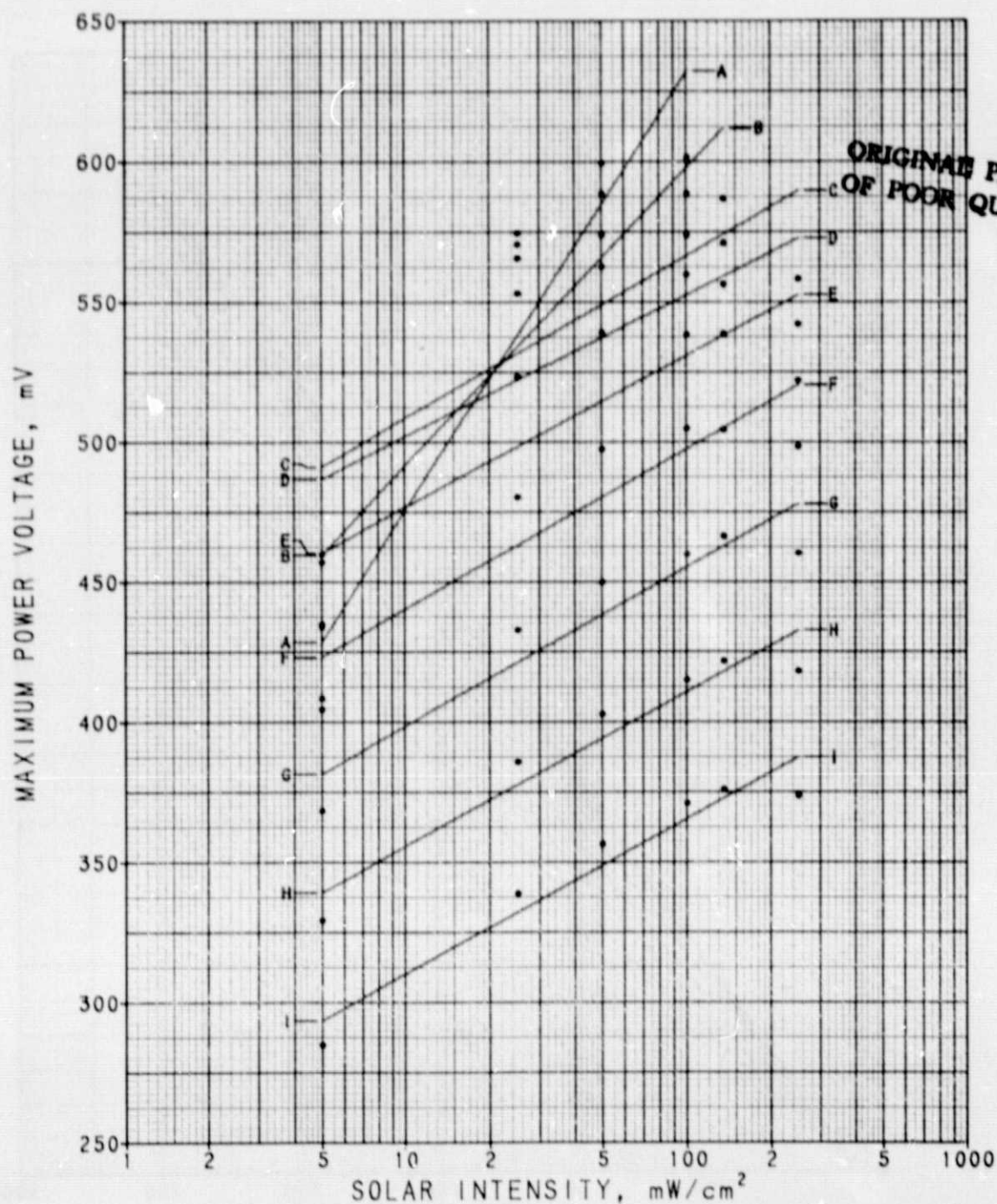
Figure 9. Average V_{∞} as a Function of Intensity



ID	°C	ID	°C
A	-100.0	I	60.0
B	-80.0		
C	-60.0		
D	-40.0		
E	-20.0		
F	.0		
G	20.0		
H	40.0		

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

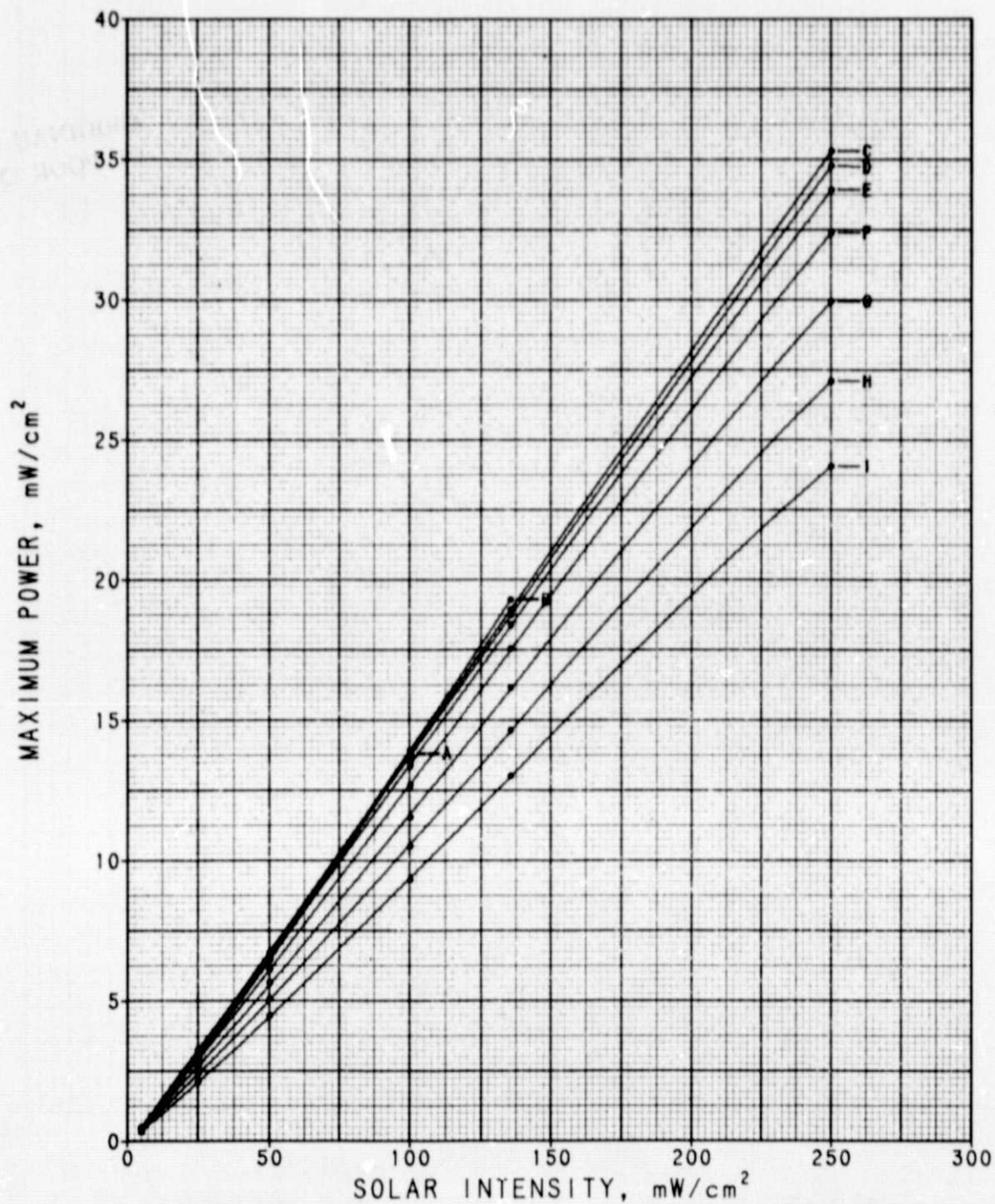
Figure 10. Average I_{mp}/cm^2 as a Function of Intensity



ID	$^{\circ}\text{C}$	ID	$^{\circ}\text{C}$
A	-100.0	I	60.0
B	-80.0		
C	-60.0		
D	-40.0		
E	-20.0		
F	0.0		
G	20.0		
H	40.0		

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

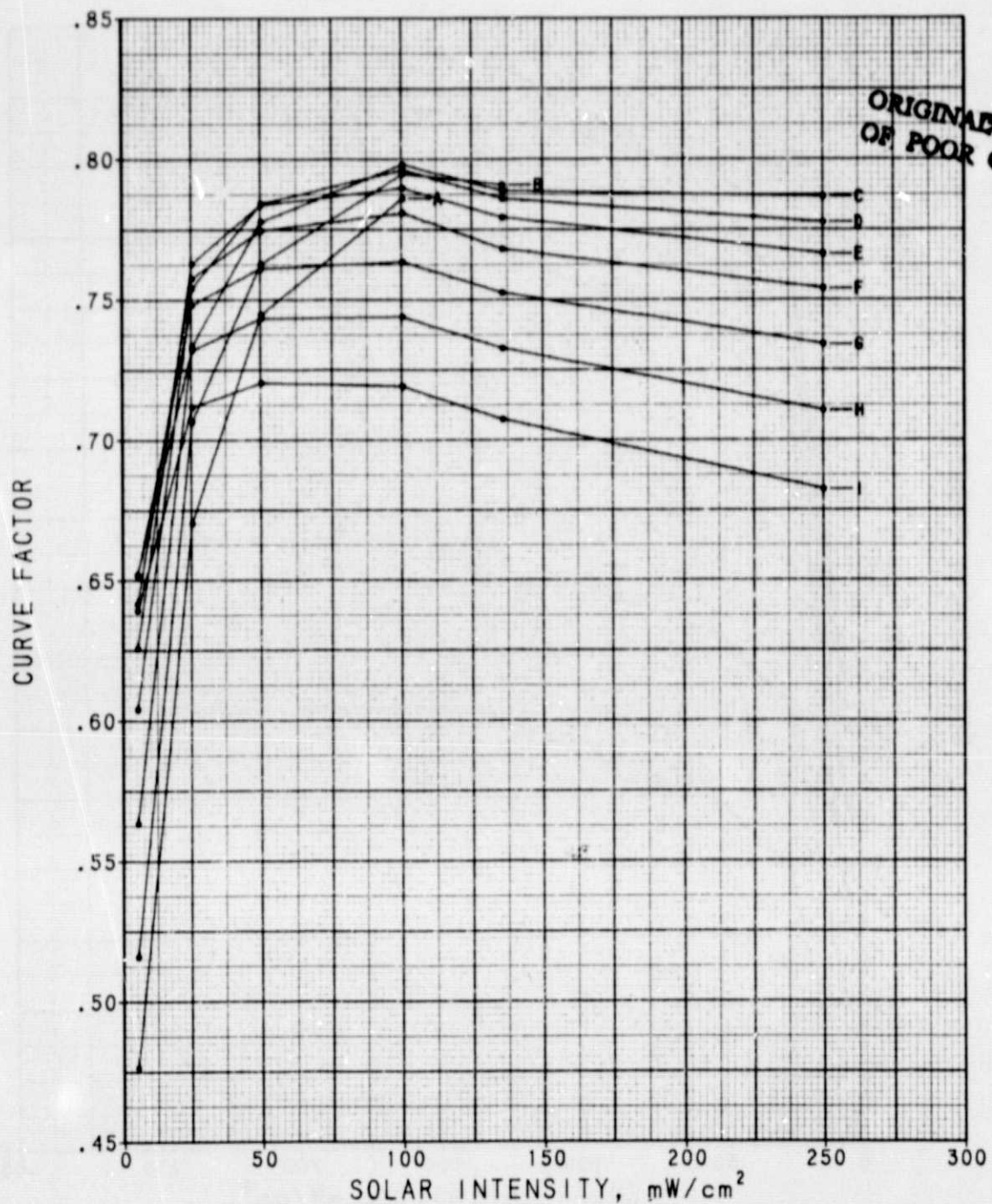
Figure 11. Average V_{mp} as a Function of Intensity



ID	°C	ID	°C
A	-100.0	I	60.0
B	-80.0		
C	-60.0		
D	-40.0		
E	-20.0		
F	0		
G	20.0		
H	40.0		

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

Figure 12. Average $P_{\max}/\text{cm}^2$ as a Function of Intensity



ID	°C	ID	°C
A	-100.0	I	60.0
B	-80.0		
C	-60.0		
D	-40.0		
E	-20.0		
F	0.0		
G	20.0		
H	40.0		

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

Figure 13. Average Curve Factor as a Function of Intensity

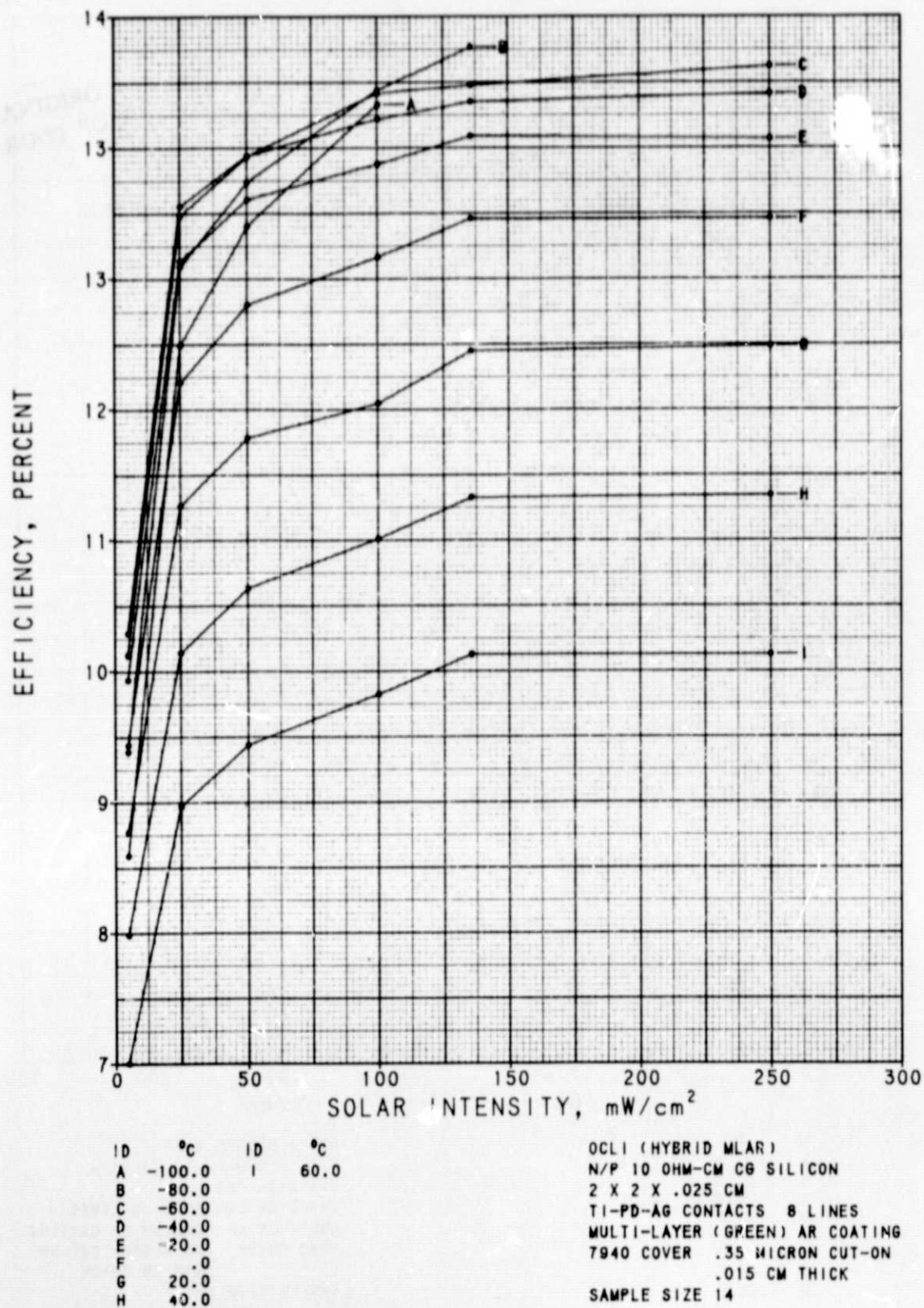


Figure 14. Average AMO Efficiency as a Function of Intensity

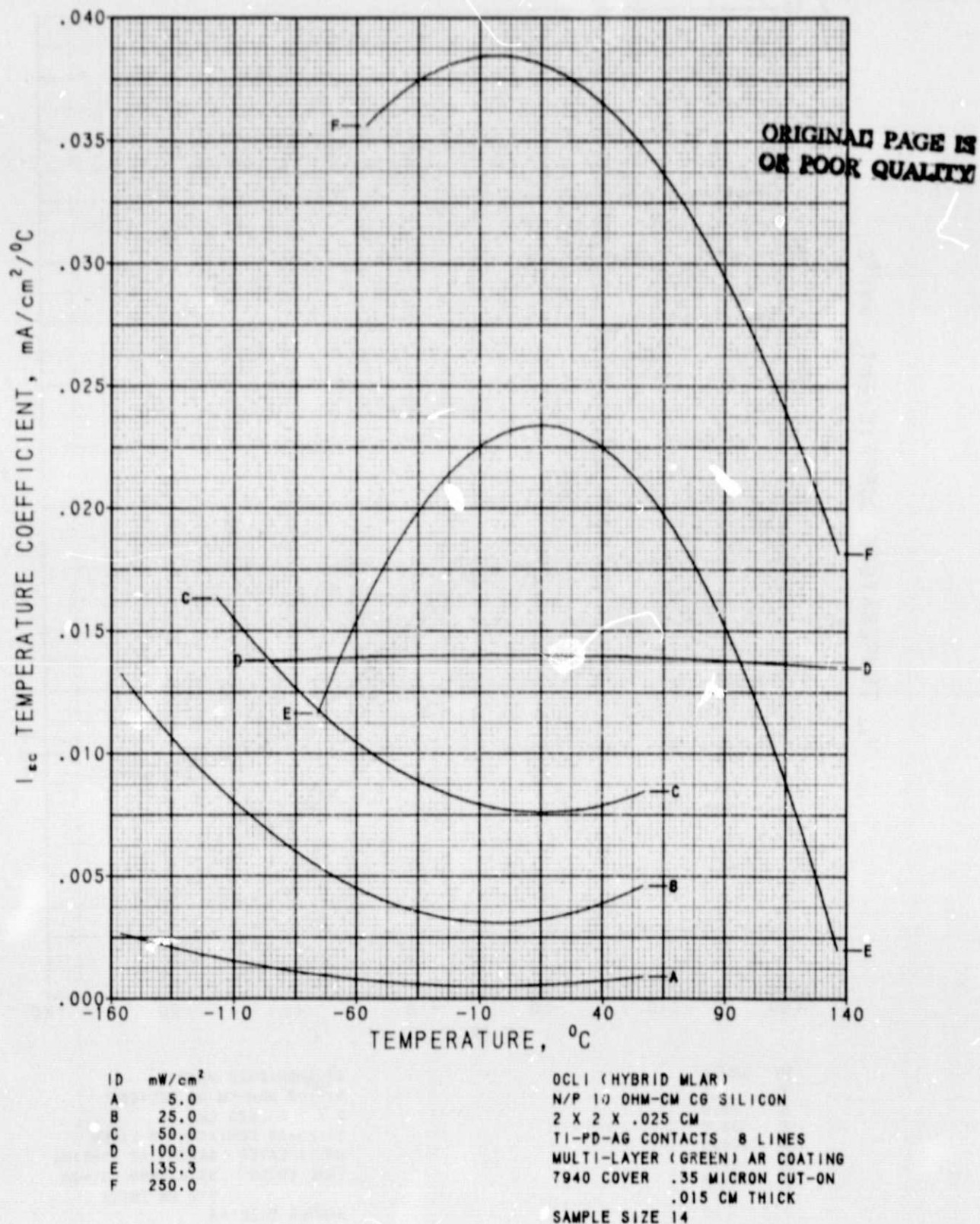
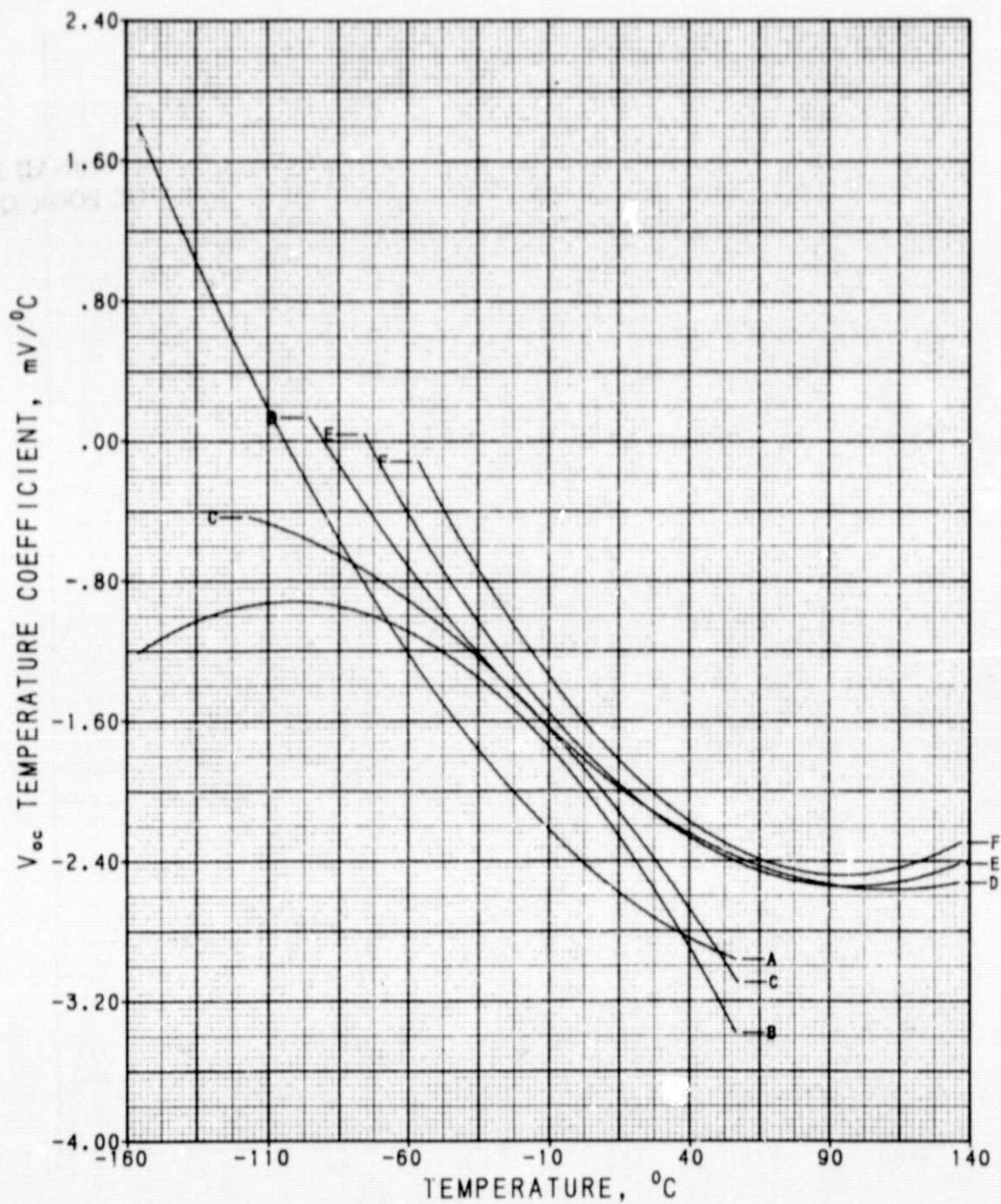


Figure 15. I_{sc} Temperature Coefficient

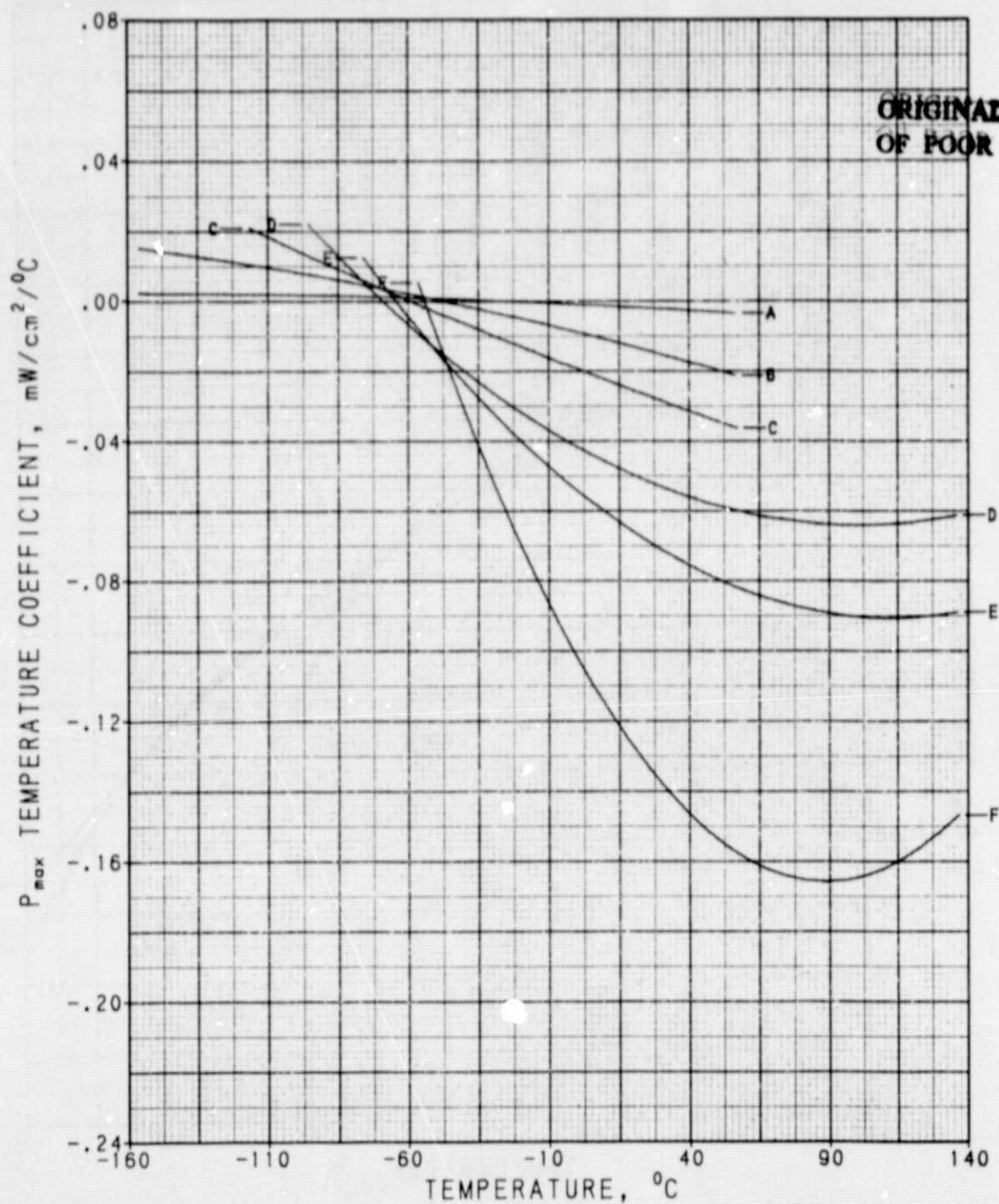


ID	mW/cm ²
A	5.0
B	25.0
C	50.0
D	100.0
E	135.3
F	250.0

OCLI (HYBRID MLAR)
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 MULTI-LAYER (GREEN) AR COATING
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 .015 CM THICK
 SAMPLE SIZE 14

Figure 16. V_{OC} Temperature Coefficient

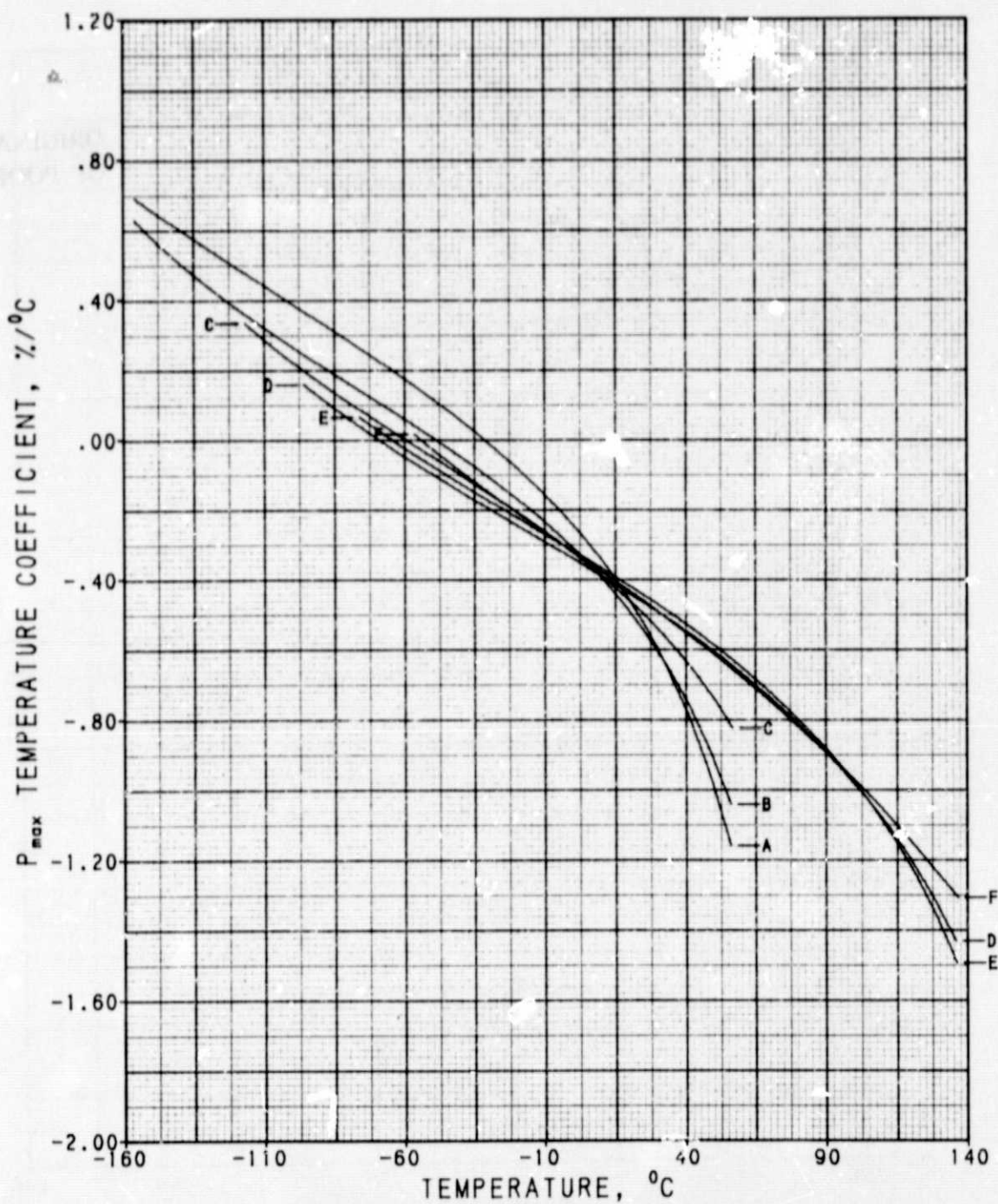
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ID	mW/cm ²
A	5.0
B	25.0
C	50.0
D	100.0
E	135.3
F	250.0

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.015 CM THICK
SAMPLE SIZE 14

Figure 17. P_{max} Temperature Coefficient



ID	mW/cm ²
A	5.0
B	25.0
C	50.0
D	100.0
E	135.3
F	250.0

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

Figure 18. P_{max} Temperature Coefficient

Table 1. Average Short Circuit Current

TABLE 1. AVERAGE SHORT CIRCUIT CURRENT, ISC (MA/CM**2)

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

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CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2)					
	5.00	25.00	50.00	100.00	135.30	250.00
-160.00	1.16 (.03)	5.83 (.16)	-	-	-	-
-140.00	1.19 (.04)	5.91 (.19)	-	-	-	-
-120.00	1.23 (.04)	6.14 (.19)	12.13 (.32)	-	-	-
-100.00	1.28 (.03)	6.44 (.15)	12.51 (.20)	25.48 (.41)	-	-
-80.00	1.30 (.02)	6.55 (.10)	12.77 (.14)	25.88 (.31)	35.72 (.42)	-
-60.00	1.32 (.01)	6.63 (.08)	12.94 (.11)	26.16 (.27)	35.69 (.36)	67.53 (.59)
-40.00	1.32 (.01)	6.66 (.07)	13.12 (.10)	26.31 (.27)	36.17 (.38)	68.43 (.47)
-20.00	1.33 (.01)	6.72 (.06)	13.31 (.08)	26.68 (.25)	36.66 (.35)	69.24 (.55)
.00	1.34 (.01)	6.77 (.07)	13.49 (.08)	26.91 (.25)	37.20 (.25)	69.90 (.52)
20.00	1.35 (.01)	6.88 (.06)	13.66 (.08)	27.07 (.24)	37.55 (.30)	70.50 (.46)
40.00	1.37 (.01)	6.97 (.07)	13.82 (.10)	27.57 (.29)	38.02 (.29)	71.25 (.48)
60.00	1.38 (.01)	7.02 (.06)	13.93 (.08)	27.85 (.27)	38.44 (.29)	72.04 (.60)
80.00	-	-	-	28.00 (.28)	38.69 (.28)	72.97 (.58)
100.00	-	-	-	28.33 (.25)	39.08 (.31)	73.29 (.45)
120.00	-	-	-	28.59 (.30)	39.43 (.31)	73.86 (.66)
140.00	-	-	-	28.86 (.26)	39.37 (.30)	74.19 (.56)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 2. Average Open Circuit Voltage

TABLE 2. AVERAGE OPEN CIRCUIT VOLTAGE: VOC (MV)

G/LI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2)					
	5.00	25.00	50.00	100.00	135.30	250.00
-160.00	623.59 (88.40)	766.82 (14.66)	-	-	-	-
-140.00	636.06 (74.97)	740.06 (11.13)	-	-	-	-
-120.00	643.26 (62.16)	714.14 (5.44)	710.39 (4.79)	-	-	-
-100.00	664.96 (29.04)	694.76 (4.82)	692.72 (5.08)	690.55 (5.24)	-	-
-80.00	662.93 (16.85)	680.50 (4.80)	679.42 (4.92)	677.62 (5.33)	683.28 (5.16)	-
-60.00	648.92 (8.93)	667.59 (4.96)	667.26 (5.52)	666.62 (5.38)	671.73 (5.53)	664.59 (5.43)
-40.00	613.47 (8.94)	649.49 (3.16)	653.07 (6.33)	654.66 (4.90)	659.20 (6.00)	653.55 (5.37)
-20.00	567.20 (9.05)	616.16 (2.46)	627.82 (4.60)	634.74 (4.61)	643.44 (3.98)	639.26 (4.81)
.00	518.46 (8.26)	570.01 (3.08)	588.74 (2.46)	602.64 (2.37)	613.57 (3.01)	614.79 (3.39)
20.00	468.94 (7.52)	522.27 (3.28)	542.47 (2.77)	558.59 (4.43)	572.06 (3.04)	578.82 (3.42)
40.00	417.99 (8.43)	472.56 (3.42)	493.26 (5.45)	512.58 (3.14)	525.94 (3.42)	535.43 (3.63)
60.00	367.69 (6.60)	423.44 (3.52)	445.24 (3.23)	465.44 (3.60)	478.98 (3.60)	489.58 (3.89)
80.00	-	-	-	417.86 (3.45)	429.77 (3.92)	441.85 (4.12)
100.00	-	-	-	367.01 (4.06)	380.98 (4.15)	394.04 (4.39)
120.00	-	-	-	318.21 (4.31)	331.59 (4.42)	345.04 (4.65)
140.00	-	-	-	267.06 (4.12)	280.05 (4.51)	296.51 (4.83)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 3. Average Maximum Power Current

TABLE 3. AVERAGE MAXIMUM POWER CURRENT, IMP (MA/CM**2)

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

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CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2)					
	5.00	25.00	50.00	100.00	135.30	250.00
-160.00	.91 (.07)	4.29 (.31)	-	-	-	-
-140.00	.93 (.07)	4.46 (.32)	-	-	-	-
-120.00	.96 (.07)	4.75 (.32)	10.09 (.53)	-	-	-
-100.00	.99 (.08)	5.22 (.30)	10.76 (.38)	23.00 (.55)	-	-
-80.00	1.02 (.06)	5.52 (.26)	11.24 (.32)	23.68 (.40)	32.89 (.45)	-
-60.00	1.05 (.07)	5.74 (.19)	11.70 (.23)	24.25 (.43)	33.12 (.32)	63.25 (.77)
-40.00	1.07 (.06)	5.90 (.16)	11.94 (.22)	24.51 (.37)	33.68 (.36)	64.16 (.95)
-20.00	1.09 (.05)	6.03 (.16)	12.16 (.19)	24.84 (.34)	34.14 (.49)	64.98 (.70)
.00	1.10 (.05)	6.09 (.14)	12.36 (.17)	25.09 (.23)	34.76 (.41)	65.00 (.91)
20.00	1.12 (.05)	6.22 (.13)	12.53 (.17)	25.11 (.26)	34.65 (.32)	65.09 (.71)
40.00	1.14 (.04)	6.24 (.11)	12.58 (.17)	25.32 (.33)	34.74 (.24)	64.82 (.80)
60.00	1.14 (.04)	6.25 (.11)	12.54 (.21)	25.12 (.28)	34.65 (.30)	64.39 (1.10)
80.00	-	-	-	24.84 (.32)	34.18 (.30)	63.61 (.90)
100.00	-	-	-	24.69 (.39)	33.75 (.36)	61.86 (.75)
120.00	-	-	-	24.11 (.44)	32.64 (.25)	60.66 (1.29)
140.00	-	-	-	23.24 (.40)	30.70 (.59)	58.12 (1.22)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 4. Average Maximum Power Voltage

TABLE 4. AVERAGE MAXIMUM POWER VOLTAGE: VMP (MV)

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2)					
	5.00	25.00	50.00	100.00	135.30	250.00
-160.00	337.57 (46.30)	550.29 (59.38)	-	-	-	-
-140.00	350.64 (47.41)	555.64 (44.73)	-	-	-	-
-120.00	374.36 (49.78)	569.14 (28.83)	606.64 (11.49)	-	-	-
-100.00	408.36 (51.33)	574.43 (17.09)	599.50 (12.57)	601.29 (4.91)	-	-
-80.00	434.86 (54.39)	570.50 (12.67)	588.50 (8.29)	588.57 (4.45)	586.79 (4.93)	-
-60.00	459.71 (39.77)	565.57 (11.30)	573.86 (6.51)	573.71 (4.41)	570.93 (2.30)	558.21 (4.23)
-40.00	456.93 (33.22)	553.07 (9.48)	562.57 (6.50)	559.71 (6.12)	556.36 (5.92)	542.07 (4.18)
-20.00	433.93 (26.86)	523.29 (9.02)	538.93 (3.47)	538.36 (4.88)	538.57 (4.78)	522.00 (4.30)
.00	404.43 (18.28)	480.36 (7.01)	497.43 (4.27)	504.79 (4.26)	504.43 (6.21)	498.43 (4.43)
20.00	368.36 (14.16)	432.79 (6.75)	450.00 (3.94)	459.79 (3.33)	466.50 (4.78)	460.29 (4.76)
40.00	329.36 (13.02)	385.86 (5.79)	402.79 (5.41)	415.14 (4.09)	421.71 (4.01)	418.21 (5.70)
60.00	284.86 (10.90)	338.86 (5.39)	356.43 (4.27)	371.07 (3.99)	375.93 (4.29)	373.79 (4.82)
80.00	-	-	-	323.93 (4.27)	330.00 (3.64)	326.79 (5.24)
100.00	-	-	-	274.00 (4.40)	283.64 (3.65)	282.79 (5.29)
120.00	-	-	-	230.14 (4.80)	238.93 (3.08)	235.71 (5.84)
140.00	-	-	-	185.79 (3.33)	194.93 (4.39)	193.36 (4.45)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 5. Average Maximum Power

TABLE 5. AVERAGE MAXIMUM POWER, P_{MAX} (MW/CM²)

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

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CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM ²)					
	5.00	25.00	50.00	100.00	135.30	250.00
-160.00	.31 (.05)	2.37 (.34)	-	-	-	-
-140.00	.33 (.05)	2.48 (.31)	-	-	-	-
-120.00	.36 (.05)	2.71 (.27)	6.12 (.35)	-	-	-
-100.00	.40 (.05)	3.00 (.21)	6.45 (.27)	13.83 (.37)	-	-
-80.00	.44 (.06)	3.15 (.17)	6.62 (.21)	13.94 (.30)	19.30 (.34)	-
-60.00	.48 (.03)	3.24 (.14)	6.72 (.17)	13.91 (.27)	18.91 (.19)	35.31 (.49)
-40.00	.49 (.05)	3.26 (.13)	6.72 (.14)	13.72 (.20)	18.74 (.18)	34.78 (.52)
-20.00	.47 (.04)	3.16 (.12)	6.55 (.13)	13.37 (.22)	18.38 (.22)	33.92 (.40)
.00	.45 (.04)	2.93 (.10)	6.15 (.12)	12.66 (.19)	17.53 (.18)	32.40 (.39)
20.00	.41 (.03)	2.69 (.08)	5.64 (.11)	11.55 (.18)	16.16 (.19)	29.96 (.44)
40.00	.37 (.02)	2.41 (.07)	5.0 ^a (.11)	10.51 (.19)	14.65 (.19)	27.11 (.54)
60.00	.33 (.02)	2.12 (.07)	4.47 (.10)	9.32 (.16)	13.02 (.18)	24.07 (.47)
80.00	-	-	-	8.05 (.18)	11.28 (.17)	20.79 (.45)
100.00	-	-	-	6.77 (.15)	9.57 (.16)	17.49 (.39)
120.00	-	-	-	5.55 (.14)	7.80 (.12)	14.30 (.39)
140.00	-	-	-	4.32 (.11)	5.98 (.17)	11.24 (.36)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 6. Average Curve Factor

TABLE 6. AVERAGE CURVE FACTOR

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2)					
	5.00	25.00	50.00	100.00	135.30	250.00
-160.00	.4277 (.0497)	.5301 (.0791)	-	-	-	-
-140.00	.4340 (.0487)	.5674 (.0736)	-	-	-	-
-120.00	.4559 (.0595)	.6181 (.0637)	.7102 (.0419)	-	-	-
-100.00	.4765 (.0554)	.6703 (.0506)	.7448 (.0327)	.7861 (.0189)	-	-
-80.00	.5160 (.0601)	.7064 (.0394)	.7629 (.0270)	.7947 (.0173)	.7909 (.0143)	-
-60.00	.5635 (.0576)	.7334 (.0295)	.7779 (.0203)	.7980 (.0147)	.7887 (.0100)	.7867 (.0098)
-40.00	.6039 (.0552)	.7541 (.0254)	.7842 (.0199)	.7963 (.0128)	.7859 (.0094)	.7777 (.0101)
-20.00	.6256 (.0536)	.7628 (.0227)	.7839 (.0159)	.7897 (.0119)	.7798 (.0080)	.7664 (.0087)
.00	.6415 (.0474)	.7577 (.0185)	.7746 (.0135)	.7810 (.0105)	.7681 (.0067)	.7539 (.0082)
20.00	.6515 (.0403)	.7482 (.0166)	.7612 (.0128)	.7636 (.0089)	.7525 (.0072)	.7341 (.0087)
40.00	.6520 (.0320)	.7320 (.0141)	.7434 (.0132)	.7438 (.0097)	.7327 (.0077)	.7106 (.0107)
60.00	.6391 (.0323)	.7118 (.0143)	.7203 (.0133)	.7191 (.0089)	.7073 (.0067)	.6824 (.0113)
80.00	-	-	-	.6878 (.0096)	.6783 (.0073)	.6447 (.0109)
100.00	-	-	-	.6507 (.0082)	.6430 (.0064)	.6057 (.0111)
120.00	-	-	-	.6098 (.0088)	.5965 (.0054)	.5609 (.0111)
140.00	-	-	-	.5604 (.0096)	.5427 (.0094)	.5109 (.0113)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 7. Average AMO Efficiency

TABLE 7. AVERAGE AMO EFFICIENCY (PERCENT)

OCLI (HYBRID MLAR)
 N/P 10 OHM-CM CG SILICON
 2 X 2 X .025 CM
 TI-PD-AG CONTACTS 8 LINES
 MULTI-LAYER (GREEN) AR COATING
 7940 COVER .35 MICRON CUT-ON
 .015 CM THICK
 SAMPLE SIZE 14

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CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2)					
	5.00	25.00	50.00	100.00	135.30	250.00
-160.00	6.18 (1.09)	9.46 (1.37)	-	-	-	-
-140.00	6.56 (1.04)	9.92 (1.23)	-	-	-	-
-120.00	7.19 (1.04)	10.83 (1.07)	12.24 (.71)	-	-	-
-100.00	8.09 (1.05)	11.99 (.85)	12.90 (.54)	13.83 (.37)	-	-
-80.00	8.88 (1.11)	12.59 (.69)	13.24 (.43)	13.94 (.30)	14.26 (.25)	-
-60.00	9.62 (1.00)	12.98 (.54)	13.43 (.33)	13.91 (.27)	13.98 (.14)	14.12 (.20)
-40.00	9.79 (.91)	13.05 (.51)	13.44 (.29)	13.72 (.20)	13.85 (.13)	13.91 (.21)
-20.00	9.43 (.86)	12.63 (.47)	13.10 (.26)	13.37 (.22)	13.59 (.16)	13.57 (.16)
.00	8.93 (.71)	11.71 (.38)	12.30 (.24)	12.66 (.19)	12.96 (.13)	12.96 (.16)
20.00	8.27 (.57)	10.76 (.34)	11.28 (.22)	11.55 (.18)	11.95 (.14)	11.98 (.17)
40.00	7.48 (.46)	9.64 (.29)	10.13 (.23)	10.51 (.19)	10.83 (.14)	10.84 (.21)
60.00	6.50 (.41)	8.47 (.26)	8.94 (.20)	9.32 (.16)	9.63 (.13)	9.63 (.19)
80.00	-	-	-	8.05 (.18)	8.34 (.13)	8.31 (.18)
100.00	-	-	-	6.77 (.15)	7.07 (.12)	7.00 (.15)
120.00	-	-	-	5.55 (.14)	5.76 (.09)	5.72 (.16)
140.00	-	-	-	4.32 (.11)	4.42 (.12)	4.50 (.14)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

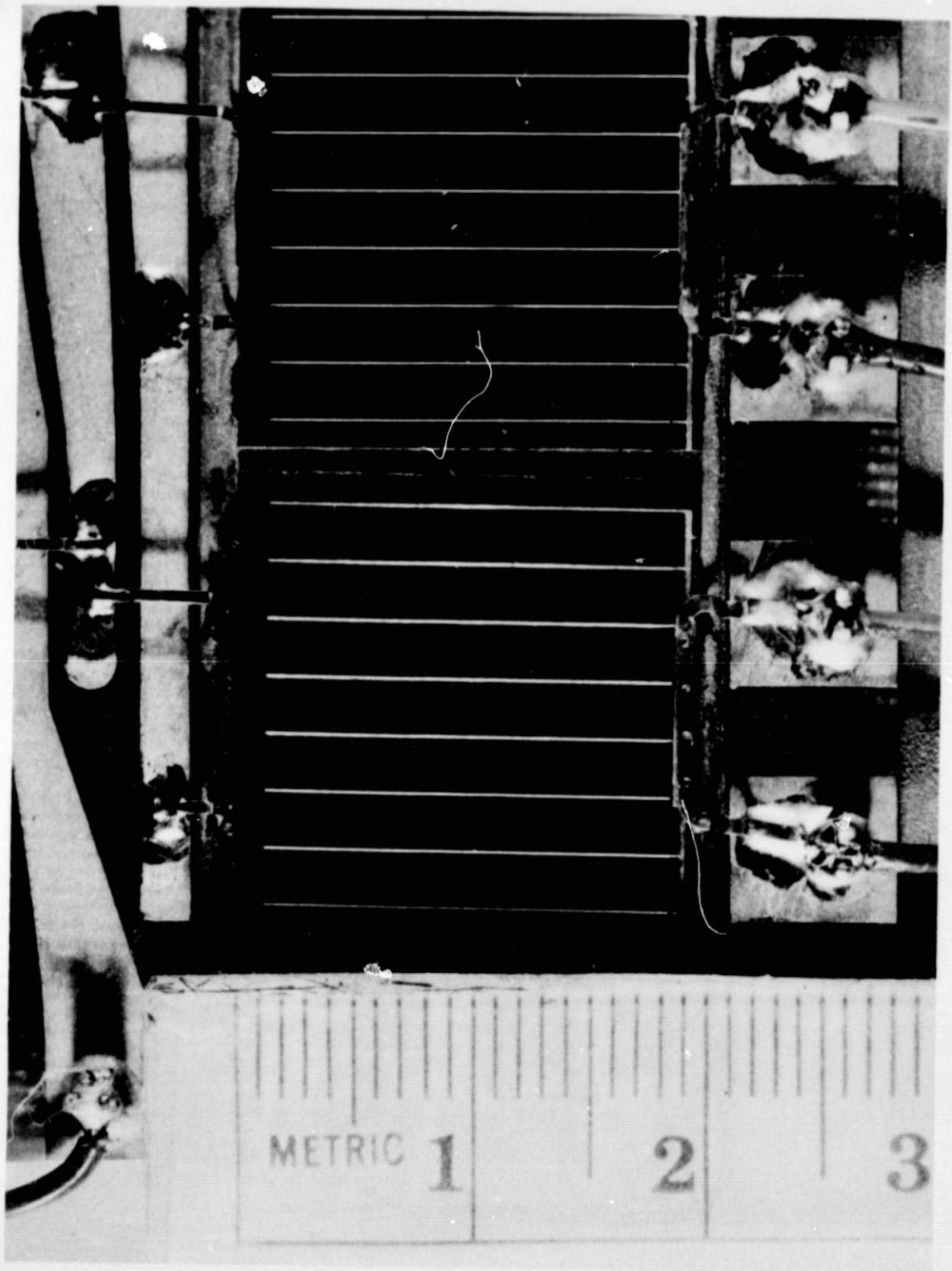


Figure A-1. Solar Cell

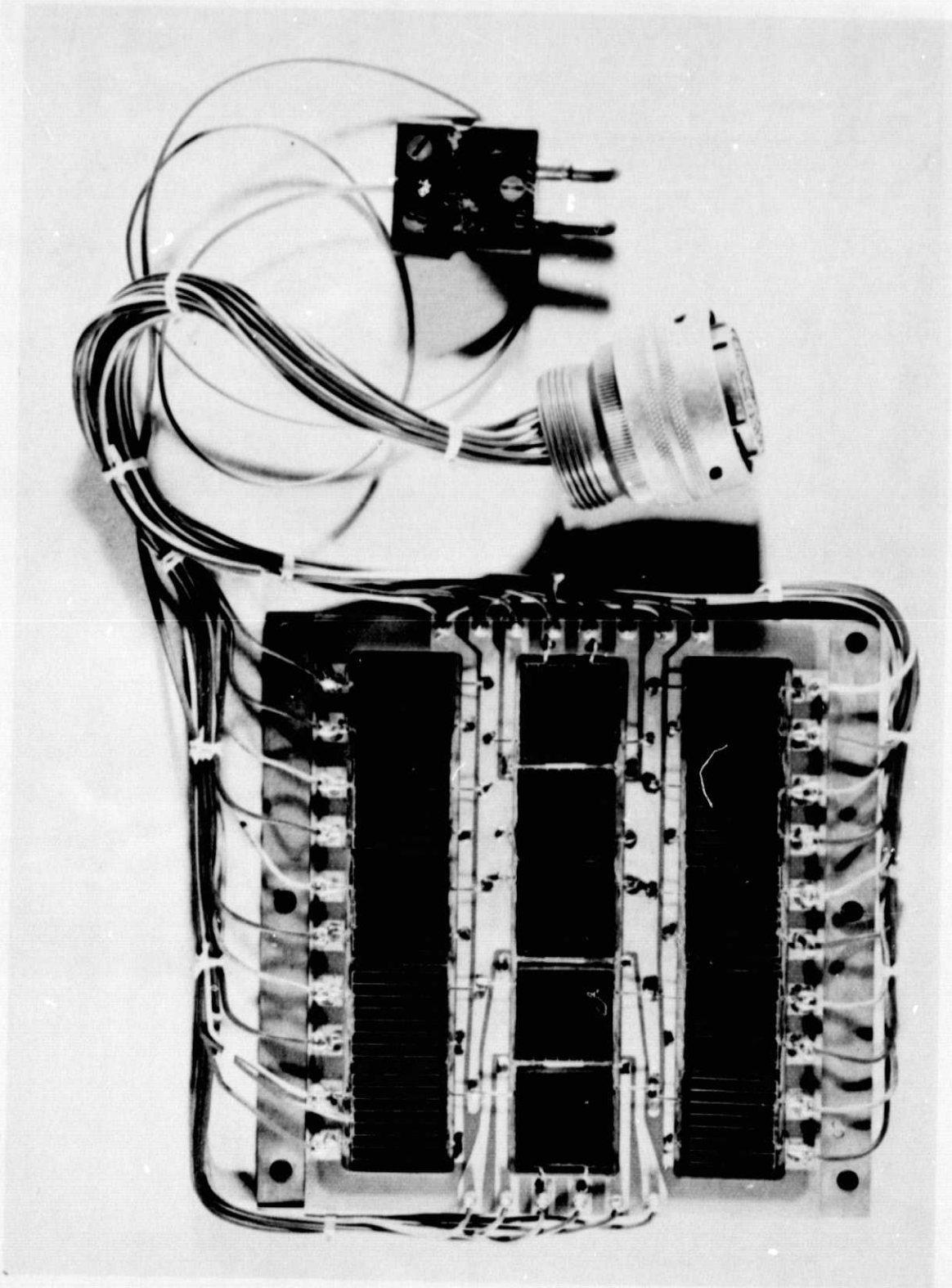


Figure A-2. Test Plate

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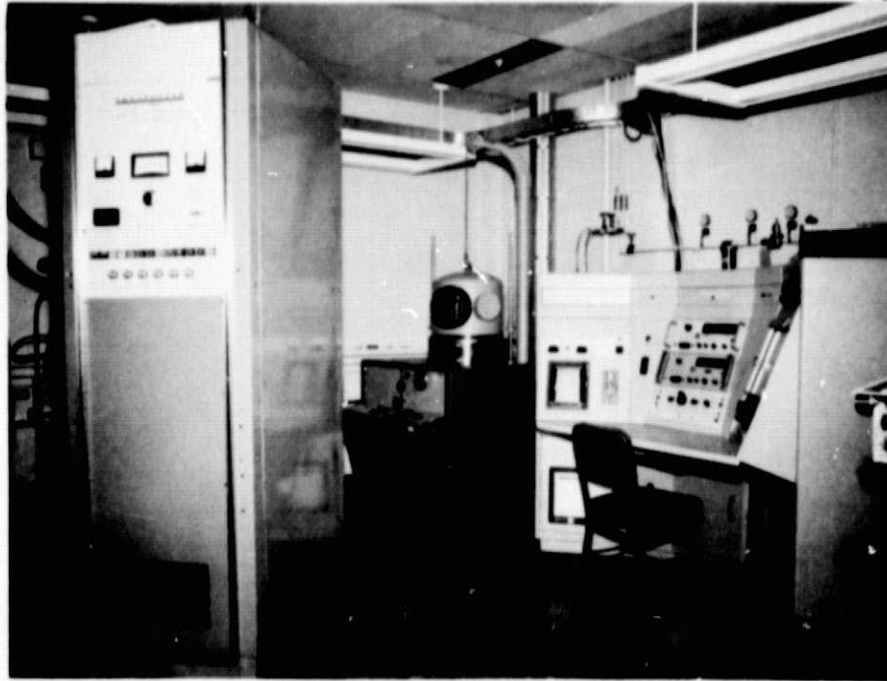


Figure A-3. Solar Cell Characterization Facility

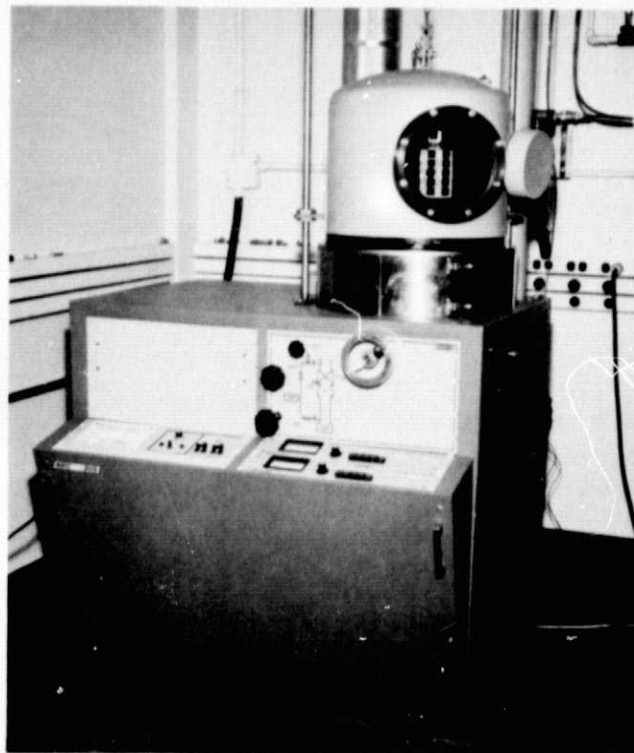


Figure A-4. Solar Cell Environmental Test Chamber